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Offset Optimizing with CTM and Genetic Algorithms: Results from Field Studies in Hannover

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Abstract

The Cell Transmission Model (CTM) by Daganzo in combination with an offset optimization algorithm based on genetic algorithms was integrated in a graphical user interface and applied to a test area in Hannover, Germany. The optimized traffic control proved a significant improvement of traffic flow considering reduction of travel time and number of stops.

Keywords: Traffic Flow Modeling; Offset Optimization; Cell Transmission Model

1. Introduction

The Cell Transmission Model (CTM) (Daganzo, 1994, 1995) is a time and space discrete traffic flow model which was originally developed to estimate traffic flow on highways. In a first step, it was proven that the CTM is basically applicable on an urban road network and in combination with an optimizer based on genetic algorithms allows for quick offset optimization (Friedrich and Almasri, 2006). The main objective of this paper was to establish a user-friendly software for offset optimization in urban road networks. The software was applied to a test area in the city of Hannover, Germany. The solutions were evaluated using microsimulations and empirical before-after studies.

The remainder of this paper is organized as follows: Formulation gives an overview about the CTM, the offset optimization and software establishment. Field Studies introduces the test area and discusses the results of the before-after studies. The paper ends with the drawn Conclusions.

2. Formulation

2.1. Cell Transmission Model

The CTM provides an approximation to the LWR model (Lighthill, Whitham, 1955; Richards, 1956) and can be used to predict transient phenomena such as build-up, propagation and dissipation of queues. It employs a simplified version of the fundamental diagram based on a trapezium form, assuming that a free-flow speed, v_f, at low densities

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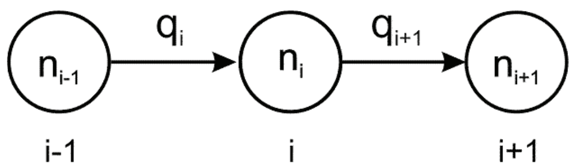

Figure 1. Cell representation for CTM

and a backward wave speed, w, for high densities are constant. Dividing the road sections into homogeneous cells i and time into homogeneous intervals of duration t such that the cell length is equal to the distance travelled by free-flowing traffic in one time interval, the LWR results are approximated by a set of recursive equations, *(1)* and *(2)*. The subscript i refers to cell i; the cell upstream and downstream is (i-1) and (i+1), respectively (Figure 1).

$$n_i(t+1) = n_i(t) + q_i(t) - q_{i+1}(t) \tag{1}$$

$$q_i(t) = \min\left(n_{i-1}(t), Q_i, w/v_f \left(N_i - n_i(t)\right)\right) \tag{2}$$

where:
n… number of vehicles
N… maximum number of vehicles
q… inflow
Q… inflow capacity

The CTM was developed for estimating traffic flow on highways, thus, one crucial drawback occurs while applying it to an urban road network: The CTM only holds for diverge flows from one predecessor cell into two successor cells and merge flows from two predecessor cells into one successor cell, respectively (Daganzo, 1994 and 1995). Thus, modeling traffic flows in a common multi-lane intersection becomes intricate. For this reason, an algorithm by Flötteröd and Rohde (2011) was implemented to the CTM which is able to model complex diverges, merges and intersections. The thus enhanced CTM is now capable of modeling cell connections with an unlimited number of predecessor or successor cells, respectively, consistent with the LWR model and with flow reductions due to right-of-way laws or signaling.

The relevant output data, i.e. delay in each cell i of the network at each time step t, can be easily calculated with the following formulas by Friedrich and Almasri (2006):

$$d_i(t) = t \cdot \left(n_i(t) - q_{i+1}(t)\right) \cdot t \tag{3}$$

where:
n_i... number of vehicles
q_{i+1}... outflow at cell i (equal to inflow at downstream cell i+1, see Figure 1)

2.2. Offset optimization

The objective for the optimization process is solving the objective function, i.e. the minimization of the overall delay in the network (sum of delays in all cells throughout the planning horizon):

$$\min f = \sum_t \sum_i d_i(t) \tag{4}$$

The objective function has an irregular shape within the solution space. For solving them, a heuristic approaches based on genetic algorithms (GA) by Almasri (2006) is used. This serial genetic algorithm (SGA) considers the relative offsets of a group of intersections one at a time. These intersections are located on traffic direction of vehicles moving from an origin to a destination. Instead of performing GA operations on the entire chromosome, only the part related to this group of intersections is considered. The remaining intersections are fixed by the optimal values found in the last iteration. However, the fitness of new chromosomes is determined by evaluating all of the network intersections and not only the group of intersections under analysis. By disconnecting the simultaneous search into a sequence of searches, the length of the chromosome in the SGA is considerably short. By shortening the chromosome, and thus the solution space, a small population of chromosomes is sufficient to find quasi-optimal offsets quickly. In the next step, the offsets of the next group of intersections are optimized. In a serial search such as this, the order in which the intersections and offsets are respectively treated and searched greatly influences the optimization results. The SGA procedure consists of the following steps:

1. Determine groups of relative offsets and their search order
2. Initialize each relative offset in each group with a value equal to the time needed to travel freely from the first intersection to the second one and binary encode this value
3. Start the GA process with the first group determined in step 1 and randomly generate a population of chromosomes encoding each solution, which represents all relative offsets in this group of intersections in the tested network
4. While termination condition is not met (e.g. a chosen number of generations):

4.1. decode chromosomes into sets of relative offsets and evaluate the fitness of all the individuals with the CTM;
4.2. put fittest chromosome into a mating pool;
4.3. produce a number of offsprings by crossover and mutation;
4.4. replace weakest chromosomes with superior offspring.

5. Fix the best relative offsets of this group and repeat steps 3 and 4 with the order determined in step 1 until all groups are finished.

3. Software establishment

The software includes four main components: Net-Editor, Traffic Signal-Editor, CTM-Control and Offset Optimizer and Output Visualization.

With the Net-Editor, the user can easily create the urban road network in a common node-link-style. The real road network can be loaded as a standardized shape file from a geographic information system (GIS) and the user may simply "trace" the simulation network to secure correct net topology. Figure 2 is a screenshot from the Net-Editor which shows the underlying road network derived from an GIS-shape file (bold grey lines) and the simulation network with links (bold blue lines) and nodes (blue dots). The thin blue lines represent "connector links" which indicate the possible turnings for the approaching flows only. They do not carry any flow (i.e. the incoming flows "hop" directly from the entry of the intersection to its exit), which is inherent to the algorithm by Flötteröd and Rohde (2011) used in the CTM. All turning ratios of the intersections entry notes are set manually by the user, the corresponding ratios of the exit nodes are set automatically (white arrows and grew arrow, respectively, in Figure 2).

The Traffic Signal-Editor provides an XML-scheme-based interface to edit all relevant traffic signal parameters for fixed-time signal controllers (Figure 3): signal group (1) with green time start and end (2,3) and related links (4), cycle time (5), initial offset (6), flow restricted left-turning flows (7) with related right-of-way links (8).

The CTM-Control and Offset Optimizer component (Figure 4) is an interface between the Net- and Traffic Signal-Editor and the CTM, which runs as an independent application within the software. The user chooses the relevant parameters: time interval (1), simulation duration (2), termination conditions (3), number of successive SGA runs (5) and population of chromosomes (6). For this application, the minimization of the overall delay in the network according to Equation *(4)* was set as optimization criteria (4), The results of the optimization criteria and the new offsets are visualized in the Net-Editor.

Regarding computation time, it should be mentioned that the software is suitable for offline applications only. Most probably, this is due to the algorithm by Flötteröd and Rohde (2011), which allows for very easy network editing but is more time consuming than the merge/diverge-formulas in the CTM by Daganzo (1995). The interested reader is referred to the work of Pohlmann and Friedrich (2010), who adopted the CTM for online offset optimization.

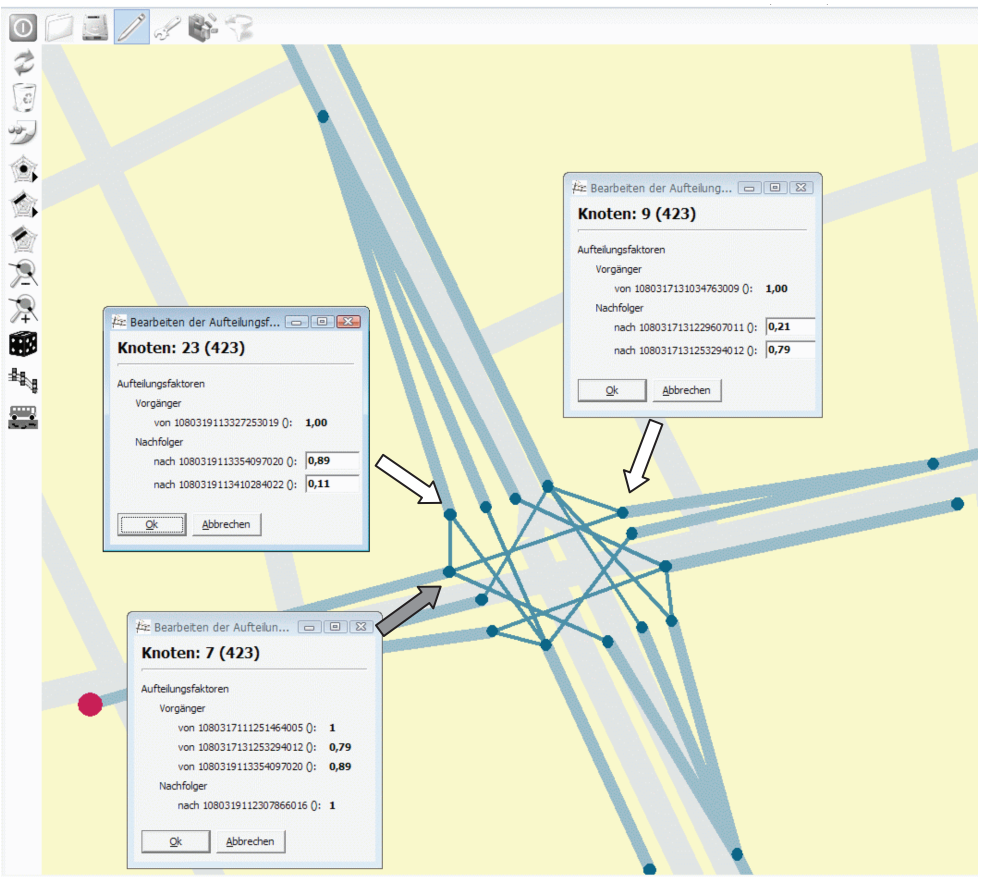

Figure 2. Net-Editor (Screenshot)

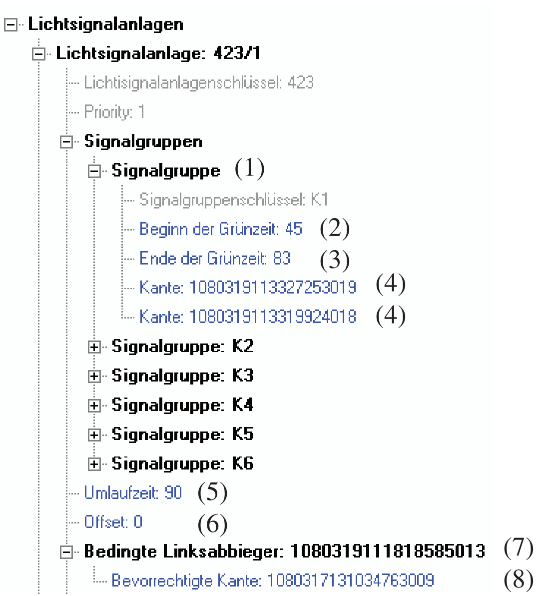

Figure 3. Traffic Signal-Editor (Screenshot)

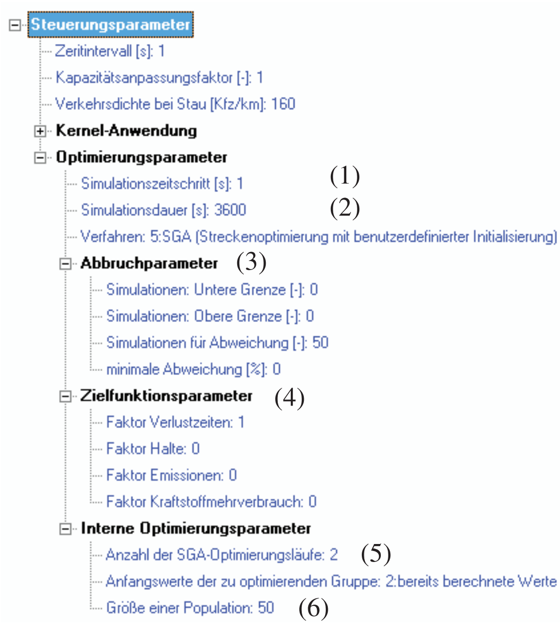

Figure 4. CTM-Control and Offset Optimizer (Screenshot)

4. Field Studies

4.1. Test area

A 1.5 km long part of Hildesheimer Straße in Hannover, Germany, was chosen as test area (Figure 5). It is an arterial which connects the city center with the highways surrounding Hannover. It has 2 lanes for both directions and 5 intersections with signal controllers (LSA), mainly with actuated traffic control. All signal controls have a cycle time of 90 s and either 3 stages (LSA 420, 423) or 2 stages (LSA 413, 421, 422). At LSA 423, a bus line crosses the Hildesheimer Straße, which public transport priority rules had to remain unchanged.

The objective of the offset optimization was to improve northbound traffic flow towards the city center in the morning peak hour from 7:30 to 8:30 a.m. Extensive traffic measurements were taken in March 2009: link and turning flows, travel times of the northbound traffic flows (i.e. from "TT Start" to "TT End" in Figure 5) via Automatic Number Plate Recognition (ANPR) and GPS-tracked floating car data (FCD). The average travel time was found to be 3:30 minutes. Traffic state within the whole test area was in free flow condition. Northbound traffic flows were between 1110 veh/h at the entrance of the test area in the south, and 1050 veh/h at the exit at LSA 420, respectively. Those data were used to build up and calibrate the test area in the microscopic traffic simulator AIMSUN NG 5.1 (TSS). It served as a virtual reality of the test area, allowing for analyzing the impact of the offset optimization solutions under laboratory conditions before testing them in the real world.

LSA 423 was declared as reference point for the relative offsets of the downstream intersections and its actuated traffic control remained unchanged. For all other intersections, simple fixed time control programs according to HBS (2001) were designed. The test area's network was edited in the Net-Editor; the fixed time control programs in the Traffic Signal-Editor, respectively. The actuated traffic control of LSA 423 was transferred into a pseudo fixed

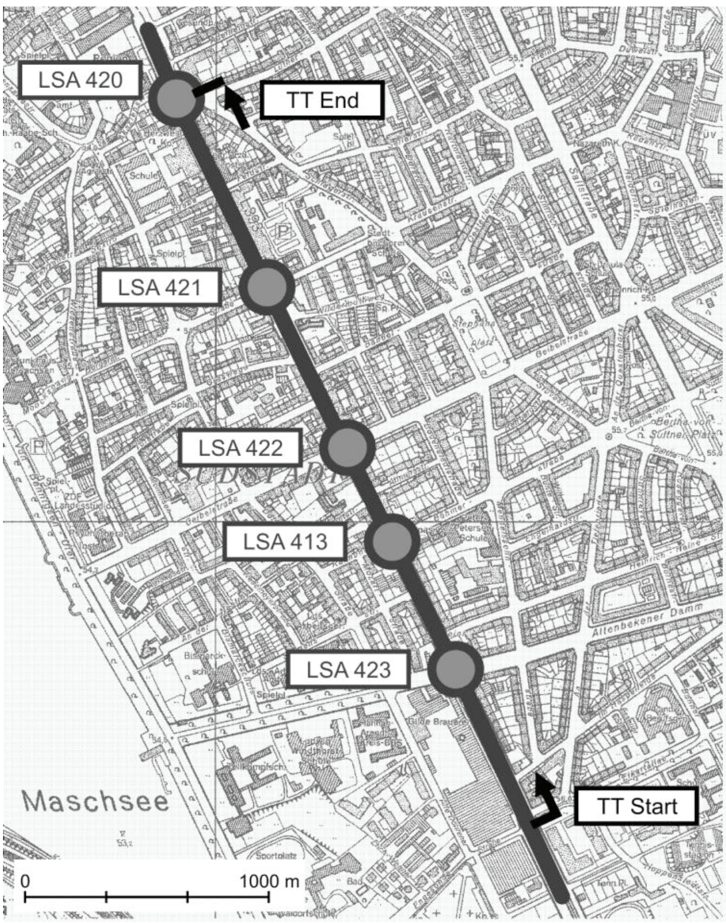

Figure 5. Test Area. Dots represent Traffic Signals, TT = Travel Time Measurement

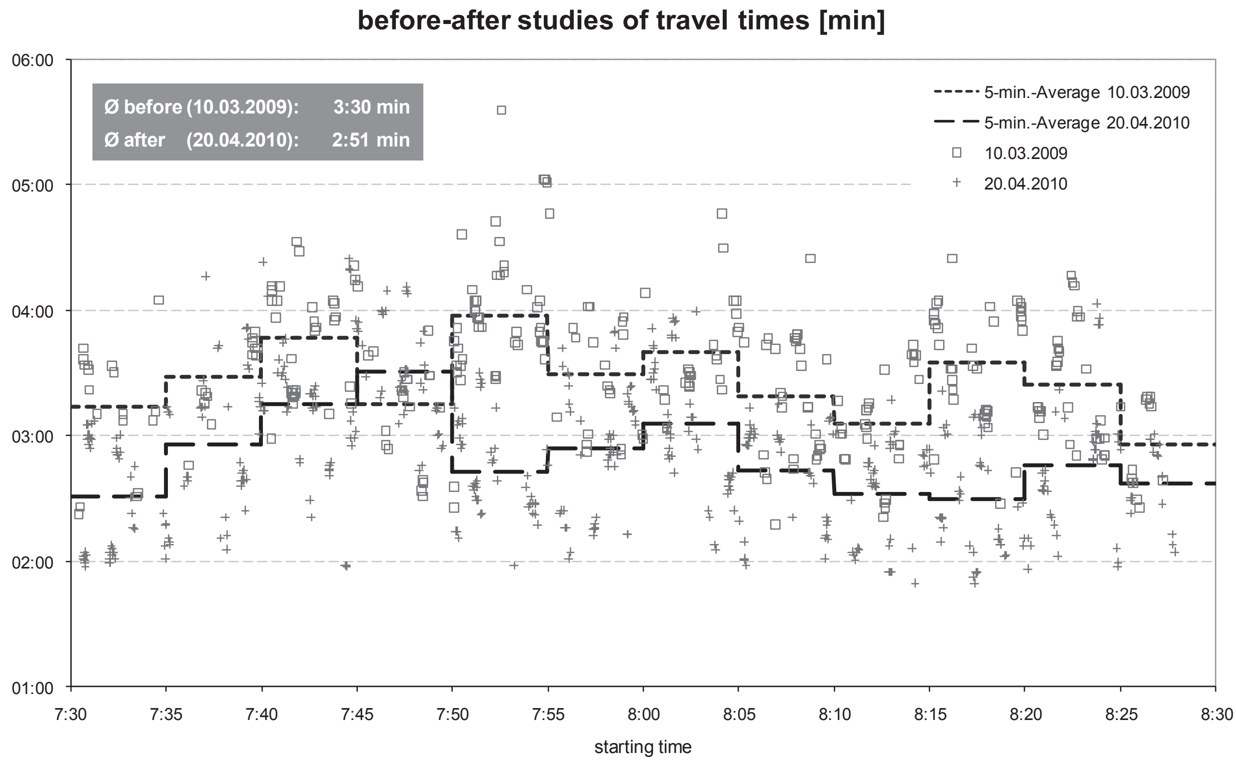

Figure 6. Before-after studies of travel times.

time program according to the average green time split. Then, the relative offsets for the northbound traffic were determined with the CTM and Offset Optimizer and tested in the virtual reality which stated a significant reduction of 28 % in travel times of the northbound traffic flows. This promising solution was implemented in the signal controllers in the test area. Again, travel times northbound and GPS-tracked floating car data were taken in April 2010. The results of the concluding before-after-studies are discussed in the following.

4.2. Before-after studies

Figure 6 depicts before-after studies of travel times taken by ANPR measurements. Overall, a significant reduction in the average travel times of northbound traffic flows in the morning peak hour can be stated, i.e. 3:30 minutes before optimization in March 2009 and 2:51 minutes after optimization in April 2010, which corresponds to a reduction of 19 %. The traffic demand was a little higher than in the before study: 1250 veh/h entered the test area and 1070 veh/h left it at LSA 420. Thus, the effects on travel times are mainly due to the change in traffic control.

A closer look on the average travel times within every 5-minute interval reveals that this holds for every interval but from 7:45 to 7:50 where police operations caused a temporal bottle neck. Obviously, this reduction could only be possible due to the fact that every driver experiences smaller delay times and number of stops, and thus is able to travel the arterial more smoothly.

Regarding the before-after studies of the GPS-tracked floating car data in Figure 7, this assumption is proved to be right. Before the optimization (March 2009), every FCD-trajectory shows at least one stop at a traffic signal en route. After optimization (April 2010), the number of stops is reduced drastically and the trajectories correspond to a smaller travel time. The few stops and delays are mainly because of the fact that intersection 423 had to keep its actuated traffic control. Inevitably, the varying green time splits in real world contradict with the offsets solutions estimated with the model.

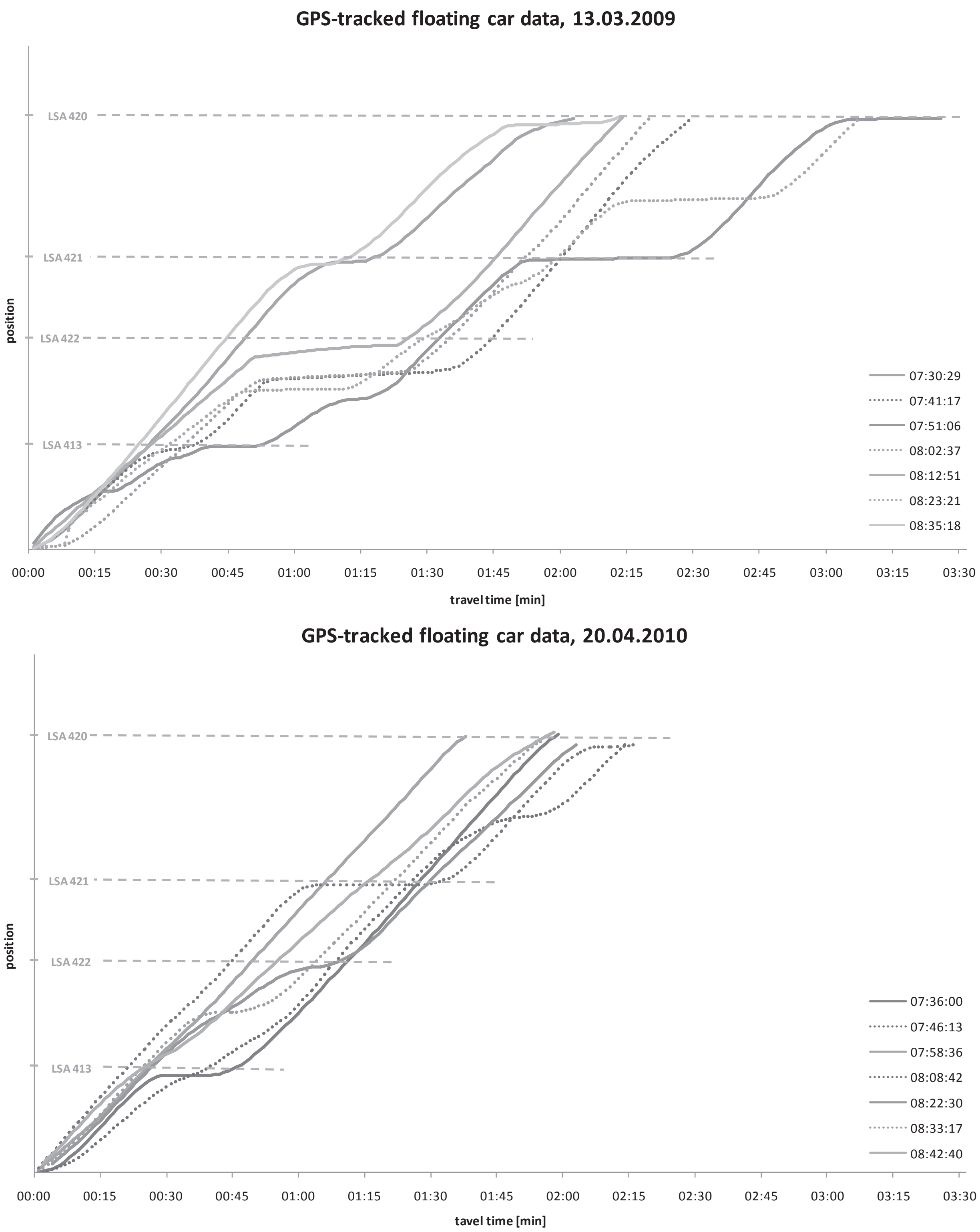

Figure 7. Before-after studies of GPS-tracked floating car data.

5. Conclusions

The enhanced CTM is able to calculate the optimization criteria needed for the offset optimization functions. The established software which combines the enhanced CTM with an offset optimizer based on a serial genetic algorithm performs well. The optimized offsets and fixed time control programs proved a reduction in travel times in the test area of 19 %, whereas AIMSUN estimated 28 %. This difference results is mainly due to difficulties in optimizing offsets between fixed time and actuated traffic controlled intersections. Further investigations are needed in order to model traffic actuated control with the CTM.

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